

TESTS OF THE EINSTEIN EQUIVALENCE PRINCIPLE USING TEV BLAZARS

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ABSTRACT

The observed time delays between different energy bands from TeV blazars provide a new interesting way of testing the Einstein Equivalence Principle (EEP). If the whole time delay is assumed to be dominated by the gravitational field of the Milky Way, the conservative upper limit on the EEP can be estimated. Here we show that the strict limits on the differences of the parameterized post-Newtonian parameter γ values are $\gamma_{\text{TeV}} - \gamma_{\text{keV}} < 3.86 \times 10^{-3}$ for Mrk 421 and $\gamma_{\text{TeV}} - \gamma_{\text{keV}} < 4.43 \times 10^{-3}$ for Mrk 501, while expanding the scope of the tested EEP energy range out to the TeV–keV range for the first time. With the small time lag from the 0.2–0.8 TeV and > 0.8 TeV light curves of PKS 2155–304, a much more severe constraint on γ differences of $\sim 10^{-6}$ can be achieved, although the energy difference is of order of \sim TeV. Furthermore, we can combine these limits on the energy dependence of γ with the bound on the absolute γ value $\gamma - 1 \sim 0.3\%$ from light deflection measurements at the optical (eV) bands, and conclude that this absolute bound on γ can be extended from optical to TeV energies.

Subject headings: BL Lacertae objects: general — gravitation

1. INTRODUCTION

The Einstein Equivalence Principle (EEP), which is one of the major pillars of general relativity and other metric theories of gravity, says that the trajectories of freely falling uncharged test bodies are independent of their internal compositions and structures. The possible violations of EEP would have significant impact on people’s understanding of nature, it is therefore important to sequentially improve the verification of its accuracy.

The validity of the EEP and general relativity in a post-Newtonian context can be characterized by limits on the numerical coefficients of the parameterized post-Newtonian (PPN) parameters, such as the parameter γ . Here γ is defined as how much space curvature produced by unit rest mass (see Will 2006, 2014, for a recent review). More specifically, one can test the accuracy of EEP and general relativity by measuring the absolute value of γ (e.g., Froeschle et al. 1997; Bertotti et al. 2003; Lambert & Le Poncin-Lafitte 2009, 2011), as well as constraining the differences of γ values for different types of massless (or negligible rest mass) neutral particles, or for the same type of particle with different energies (e.g., Krauss & Tremaine 1988; Longo 1988; Gao et al. 2015; Wei et al. 2015), since general relativity predicts $\gamma \equiv 1$ and all gravity theories incorporating the EEP also predict $\gamma_1 = \gamma_2 \equiv \gamma$, where the subscripts correspond to two different test particles.

Determinations of the absolute γ values have reached high precision from light deflection and time delay measurements. The light deflection measurements from the very-long-baseline radio interferometry yielded $\gamma - 1 = (-0.8 \pm 1.2) \times 10^{-4}$ (Lambert & Le Poncin-Lafitte 2009, 2011). Through the time delay measurements of a radar signal from the Cassini spacecraft, Bertotti et al. (2003) obtained an accurate determination of $\gamma - 1 = (2.1 \pm$

$2.3) \times 10^{-5}$. These results are in good agreement with the prediction of general relativity.¹ On the other hand, some astronomical sources have been used to test the EEP by comparing the γ values for different test particles in a few instance, including the following representative cases: Krauss & Tremaine (1988) and Longo (1988) proposed that the observed time delay of the neutrinos and photons from supernova 1987A provides a new test of the EEP, they presented an upper limit on γ differences of 0.34% for neutrinos and photons, and a more severe limit of 1.6×10^{-6} for neutrinos ranging in energy from 7.5 to 40 MeV; Gao et al. (2015) used the time delays between correlated photons from gamma-ray bursts (GRBs) to constrain the accuracy of the EEP and found that the differences of the γ values for photons over the MeV–GeV or eV–MeV range is as low as $\sim 10^{-7}$, improving the limits from supernova 1987A by at least one order of magnitude; and Wei et al. (2015) proved that fast radio bursts (FRBs) of extragalactic origin can serve as an ideal testbed to probe the EEP and set the most stringent limit on γ differences up to now, yielding $\sim 10^{-8}$, by analyzing the arrival time delay of FRB photons of different frequencies, which is at least 10 to 100 times tighter than the constraints from supernova 1987A and GRBs.

It is well known that blazars are an extreme subclass of active galactic nuclei, which can be further divided into flat spectrum radio quasars if they have strong emission lines and BL Lacertae objects if they have weak or no emission lines (e.g., Ulrich et al. 1997). Blazars are characterized by broadband non-thermal emission extending from radio up to high-energy and very-high-energy (VHE) gamma-rays, and display of violent variability on

¹ Note that some other gravitational theories besides general relativity also predict $\gamma \equiv 1$ (Will 1993).

different timescales from minutes to years (e.g., Wagner & Witzel 1995). The broadband radiation is produced by a relativistic jet pointed along the line of sight (e.g., Begelman et al. 1984; Urry & Padovani 1995). Because of their fast flux variability, cosmological distances, and VHE photons in the TeV range, TeV blazars have been deemed as an effective way to probe the effect of Lorentz invariance violation (LIV; e.g., Biller et al. 1999; Aharonian et al. 2008; MAGIC Collaboration et al. 2008; H.E.S.S. Collaboration et al. 2011). Here, we suggest that TeV blazars can also provide a good astrophysical laboratory to constrain the EEP, which can further extend for the first time the scope of the tested energy range out to TeV energies.

It is worth pointing out that testing the EEP with both GRBs and TeV blazars is of great fundamental interest. GRBs can be detected out to very high redshifts ($z \sim 8.2$), but with very few high energy ($E > \text{GeV}$) photons. On the contrary, TeV blazars can be well observed by ground based detectors with large statistics of photons above a few tens of TeV. But, since high energy photons would be absorbed by extragalactic background light, TeV observations are limited to sources with low redshifts. Hence, GRBs and TeV blazars are mutually complementary in constraining the EEP, and they enable us to test different redshift and energy ranges. In this work, we first try to test the accuracy of the EEP using TeV blazars. The rest of this paper is arranged as follows. In Section 2, we briefly describe the method of testing the EEP. The constraints on the EEP from TeV blazars are showed in Section 3. Finally, we summarize our conclusions in Section 4.

2. METHOD DESCRIPTION

The observed time delays between different energy bands from the cosmological sources have been used to set bounds on the EEP. In principle, the observed time delay (Δt_{obs}) (Gao et al. 2015; Wei et al. 2015)

$$\Delta t_{\text{obs}} = \Delta t_{\text{int}} + \Delta t_{\text{LIV}} + \Delta t_{\text{spe}} + \Delta t_{\text{DM}} + \Delta t_{\text{gra}} \quad (1)$$

has contributions from the intrinsic time lag (Δt_{int}), the LIV induced time delay (Δt_{LIV}), the possible time delay due to the non-zero mass of photons in special relativity (Δt_{spe}), the underlying time delay arising from the dispersion by the line-of-sight free electron content (Δt_{DM}), and the travel time delay (Δt_{gra}) between energy bands E_1 and E_2 , caused by an external gravitational potential $U(r)$, respectively. Among these terms,

$$\Delta t_{\text{gra}} = \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_o}^{r_e} U(r) dr \quad (2)$$

is the relevant one to probe the EEP. Here, γ is the PPN parameter, r_o and r_e represent locations of Earth and source. For high energy photons, such as the gamma-ray signals considered here, Δt_{DM} is absolutely negligible. In addition, considering that both Δt_{LIV} and Δt_{spe} are also negligible for the analysis of this work, and assuming $\Delta t_{\text{int}} > 0$, one can derive

$$\Delta t_{\text{obs}} > \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_o}^{r_e} U(r) dr. \quad (3)$$

We refer the reader to Gao et al. (2015) for more details.

Generally, $U(r)$ should have three components, i.e., $U(r) = U_{\text{MW}}(r) + U_{\text{IG}}(r) + U_{\text{host}}(r)$, including the gravitational potentials of the Milky Way, intergalactic background, and host galaxy of the cosmological source, respectively. Although the potential models of $U_{\text{IG}}(r)$ and $U_{\text{host}}(r)$ are hard to know, it is plausible to assume that the effect of these two components is much greater than if we just consider the potential of the Milky Way $U_{\text{MW}}(r)$. Adopting the Keplerian potential for the Milky Way, it would be reasonable to have

$$\gamma_1 - \gamma_2 < \Delta t_{\text{obs}} \left(\frac{GM_{\text{MW}}}{c^3} \right)^{-1} \ln^{-1} \left(\frac{d}{b} \right), \quad (4)$$

where $M_{\text{MW}} \simeq 6 \times 10^{11} M_{\odot}$ is the total mass of the Milky Way (McMillan 2011; Kafle et al. 2012), b represents the impact parameter of the rays, and d denotes the distance from the Earth to the source.

3. TESTS ON THE EEP FROM TEV BLAZARS

As we know, mankind's view of nature would be greatly affected if the EEP is violated. Thus, it is important to constantly test the validity of the EEP with all kinds of alternative astronomical sources. We continue to search for such sources and propose that TeV blazars are a new interesting tool for constraining the EEP, while extending the tested EEP energy range out to TeV energies (more on this below). As examples, we use three famous TeV blazars (Mrk 421, Mrk 501, and PKS 2155-304) to constrain the EEP accuracy.

3.1. Mrk 421

Markarian 421 (Mrk 421; $z = 0.031$) is the first extragalactic TeV blazar to be detected at gamma-ray energy $E > 500 \text{ GeV}$ (Punch et al. 1992), with coordinates (J2000) R.A. = $11^{\text{h}}04^{\text{m}}19^{\text{s}}$, Dec. = $38^{\circ}11'41''$.² Using the High Altitude Gamma Ray (HAGAR) telescope array, Shukla et al. (2012) observed Mrk 421 in its high state of flux activity during February 13–19, 2010 and also detected a very bright flare above 0.25 TeV. They investigated the correlation between light curves of different energies with the cross-correlation function and found that VHE gamma-ray ($> 0.25 \text{ TeV}$) flux reaches peak with a 1.3 days lag compared with the peak time of X-ray (1.5–12 keV) flare. With the measured time delay $\Delta t_{\text{obs}} = 1.3$ days and location information, we thus obtain EEP constraint from Equation (4) for Mrk 421

$$\gamma_{\text{TeV}} - \gamma_{\text{keV}} < 3.86 \times 10^{-3}. \quad (5)$$

3.2. Mrk 501

The TeV blazar Markarian 501 (Mrk 501) is a nearby, bright X-ray emitting source at $z = 0.034$, also well known to emit VHE ($E \geq 100 \text{ GeV}$) gamma-ray photons (Quinn et al. 1996), with coordinates (J2000) R.A. = $16^{\text{h}}53^{\text{m}}52.2^{\text{s}}$, Dec. = $39^{\circ}45'36''$. Furniss et al. (2015) reported on multiwavelength observational campaign of Mrk 501 between 2013 April 1 and August 10, including the first display of hard X-ray variability with *Swift* and *NuSTAR*. The discrete correlation function

² The location information of TeV blazars are available in the TeGeV Catalogue at <http://www.asdc.asi.it/tgevcatalog/>.

was applied to study the cross-correlations between different energy bands. A time lag of 0 ± 1.5 days was measured between the VHE observations (> 0.2 TeV) and the 0.3–3 keV *Swift*/XRT band. To be conservative, we adopt the largest value 1.5 days as the time delay Δt_{obs} between these two energy bands. With the above information of Mrk 501, a severe limit on the EEP from Equation (4) is

$$\gamma_{\text{TeV}} - \gamma_{\text{keV}} < 4.43 \times 10^{-3}. \quad (6)$$

3.3. PKS 2155-304

The source PKS 2155-304 is one of the brightest TeV blazars and located at $z = 0.117$, almost four times more distant than Mrk 421 and Mrk 501. It was discovered at the radio bands as part of the Parkes survey (Shimmins & Bolton 1974), and identified as a BL Lacertae object by Hewitt & Burbidge (1980), with coordinates (J2000) R.A. = $21^{\text{h}}58^{\text{m}}52.6^{\text{s}}$, Dec. = $-30^{\circ}13'18''$. The observation of the VHE flare of PKS 2155-304 on July 28, 2006 by the High Energy Stereoscopic System (H.E.S.S.) provides the current best limit on LIV derived from the observation of blazars (H.E.S.S. Collaboration et al. 2011). Aharonian et al. (2008) determined the time delay from two light curves in different energies using the modified cross correlation function. In order to keep good photon statistics in both two energy bands, while optimizing the energy gap between the two, the correlation analysis was performed on the light curves between 0.2–0.8 TeV and > 0.8 TeV. A 95% confidence limit on a linear energy dispersion of 73 s TeV^{-1} is thus given. Since the mean difference of the photon energies between these two bands is 1.0 TeV, the dispersion per energy can be transformed to the measured time delay $\Delta t_{\text{obs}} = 73 \text{ s}$. From Equation (4), we can tighten the constraint on the EEP to

$$[\gamma(0.2 \text{ TeV} - 0.8 \text{ TeV}) - \gamma(> 0.8 \text{ TeV})] < 2.18 \times 10^{-6} \quad (7)$$

for PKS 2155-304, which is as good as the results on supernova 1987A from Longo (1988).

4. SUMMARY AND DISCUSSION

The accuracy of the EEP at the post-Newtonian level can be tested through the relative differential variations of the PPN parameters, such as the parameter γ . Inspired by the work of Gao et al. (2015), we continue to search for other alternative astronomical sources that are suitable for testing the EEP accuracy. In this work, we propose that TeV blazars can serve as a new good candidate for this purpose. Furthermore, GRBs and TeV blazars are complementary to each other in constraining the EEP, since they are observed in different energy and redshift ranges and with different levels of variability.

Using the observed time delay $\Delta t \sim 1.5$ days for the light curves with energy bands of keV to TeV and a assumption that the time delay is dominated by the gravitational potential of the Milky Way, we place robust limits on γ differences for two TeV blazars, i.e., $\gamma_{\text{TeV}} - \gamma_{\text{keV}} < 3.86 \times 10^{-3}$ for Mrk 421 and $\gamma_{\text{TeV}} - \gamma_{\text{keV}} < 4.43 \times 10^{-3}$ for Mrk 501. On the basis of the time delay from two light curves between 0.2–0.8 TeV and > 0.8 TeV bands, we can tighten the limit on γ differences to $[\gamma(0.2 \text{ TeV} - 0.8 \text{ TeV}) - \gamma(> 0.8 \text{ TeV})] < 2.18 \times 10^{-6}$ for PKS 2155-304, but the energy difference is of order of \sim

TeV. It should be underlined that these upper limits are based on very conservative estimates of the observed time delay and the total gravitational potential. The inclusion of contributions from the neglected components in the observed time delay (see Equation 1) could improve these limits in some degree. In addition, if we have a better understanding of the host galaxy and the intergalactic gravitational potential and these two effects are taken into considered, our constraint results would be significantly improved by orders of magnitude.

In the past, tests of the EEP through the differences of the γ parameter have been made of emissions from supernova 1987A (Krauss & Tremaine 1988; Longo 1988), GRBs (Sivaram 1999; Gao et al. 2015), and FRBs (Wei et al. 2015). In particular, the observation of FRBs not only provided the most stringent limits on the accuracy of the EEP, showing that the EEP is obeyed to the level of $\sim 10^{-8}$, but also extended the EEP tested energy range down to the radio band (Wei et al. 2015). Also, Gao et al. (2015) extended the tested energy range up to the MeV–GeV and eV–MeV range with the help of high energy photons from GRBs, although the capability of GRBs for testing the EEP ($\sim 10^{-7}$) was not so strong as that of FRBs. In the present paper, we prove that TeV blazars are a new support tool for probing the EEP in different energy and redshift ranges, and we derive the upper limits of $\sim 10^{-3}$ for light curves over the TeV–keV range and of $\sim 10^{-6}$ for light curves over an energy range between 0.2–0.8 TeV and above 0.8 TeV. Although our constraints on the EEP accuracy are not as tight as previous results of GRBs or FRBs, the tested energy range can be further extended out to the TeV–keV range by using the measured time delays of TeV blazars.

As mentioned above, the most precise limits on the absolute γ value of photons yield an agreement with general relativity of $\gamma - 1 \sim 10^{-5}$, which is from radio photons (Bertotti et al. 2003). And the light deflection measurements using the Hipparcos optical astrometry satellite have reached $\gamma_{\text{eV}} - 1 \sim 0.3\%$ (Froeschle et al. 1997). On the other hand, by constraining the differences of γ values between various energies, Gao et al. (2015) found that the absolute γ values of MeV or GeV photons differ from that of optical (eV) photons by $< 10^{-7}$, and our results show that the absolute γ values of TeV photons differ from that of keV photons by $< 10^{-3}$. Combining these results, we can predict that the limits on the absolute γ values of TeV photons should also be consistent with general relativity to the same level of $\sim 0.3\%$, i.e., $\gamma_{\text{TeV}} - 1 \sim 0.3\%$. We therefore conclude that this absolute bound on γ can be extended from the optical to the TeV range, and the value of γ is identical for photons between optical and TeV to within approximately 10^{-3} .

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